LATERAL DISPLACEMENT RESPONSE OF PILES INSTALLED IN NEAR SURFACE IMPROVED COARSE-GRAINED SOILS

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ABSTRACT: Piles especially for near-shore and offshore foundations frequently penetrate through loose soil deposits which are prone to excess displacement at ground level under lateral loads. Padmavathi et al. (2007) presented analysis of single rigid free head pile in cohesionless soils based on kinematics and subgrade reaction approach. In this paper, the effect of increase in stiffness by densification of the surficial cohesionless soil on the behaviour of rigid pile based on kinematics and non-linear subgrade response with hyperbolic model has been studied. The reduction in the displacement of the pile at the surface due to increase in the stiffness of the near surface soil as a consequence of densification is quantified.

1. INTRODUCTION

Piles are commonly selected as an option for the support of high-rise structures, highway and infrastructure. These structural members are often subjected to considerable lateral forces such as due to wind loads in hurricane prone areas, earthquake loads in areas of seismic activity, and wave loads in offshore environments. Hansen (1961), Broms (1964a), Meyerhof et al. (1981), Prasad & Chari (1999), Zhang et al. (2005), etc., proposed theories for the estimation of ultimate capacities of piles, piers and poles in cohesionless soils under various pile-head and base conditions.

Padmavathi et al. (2007) presented analysis of single rigid free head pile in cohesionless soils based on kinematics and subgrade reaction approach. With the same considerations as mentioned above, the effect of increase in stiffness of the surficial soil due to densification on the behaviour of rigid pile using hyperbolic approach has been studied. In this analysis, both subgrade modulus and ultimate soil pressure vary linearly with depth. Another important consideration in this analysis is that the soil does not mobilize any pressure close to the point of rotation because the displacement there is zero.

2. PROBLEM DEFINITION

A rigid pile of length, \( L \), and diameter, \( d \), is installed in a coarse grained soil. A lateral force, \( H \), is acting at an eccentricity, \( e \), which creating a moment, \( M = eH \), at the ground level (Fig. 1(a)). The pile is unrestrained and rotates through an angle, \( \theta \), about a point, ‘O’ at depth, \( z_0 \), from the ground surface. The displacement at ground line is \( \rho_0 \) due to the rotation of the pile. Modulus of horizontal subgrade reaction, \( k_{sv} \), ultimate lateral soil pressure, \( q_{max} \), unit weight, \( \gamma \), angle of internal friction, \( \phi' \), are the relevant properties of the soil. The displacements at ground level may be too high from structural considerations in many of the cases. The near surface soil can be densified so that the soil modulus increases in that portion and the displacements get reduced. The modulus and maximum soil pressure for the improved soil over the depth, \( L_{ds} \) from ground level are considered as \( k_{sd} \) and \( q_{maxd} \) respectively (Fig. 1b).

Fig. 1: (a) Original Ground (b) Improved Soil Layer near the Ground Surface
2.1 Variations of Stiffness and Strength of the Soil

The displacements vary linearly with depth. The response of the soil on to the pile is represented by non-linear Winkler type response with modulus of horizontal subgrade reaction, \( k_{so} \), and ultimate lateral soil pressure, \( q_{maxo} \). The lateral stress, \( q \), is related (Fig. 2) to the lateral displacement, \( \rho_z \), as

\[
q = k_{so} \rho_z / (1 + k_{so} \rho_z / q_{maxo})
\]

where \( \rho_z \) is the displacement of the pile at depth, \( z \), from ground surface. Both \( k_{so} \) and \( q_{maxo} \) are assumed to increase linearly with depth as shown in Figures 3(a) & (b) respectively.

\[
k_{so} = \alpha_{so} z / L
\]

and

\[
q_{maxo} = \alpha_{qo} z / L
\]

where \( \alpha_{so} \) and \( \alpha_{qo} \) are the rates of increase of the modulus of horizontal subgrade reaction and the maximum lateral soil pressure with depth respectively. The depth to the point of rotation, \( z_0 \), and the angle of rotation, \( \theta \), of the pile are the two unknowns. For equilibrium, the applied lateral force, \( H \), is equated to the total response from the soil as,

\[
H = \int_0^{z_0} k_{so} \rho_z dz - \int_0^{z_0} \frac{k_{so} \rho_z}{q_{maxo}} dz
\]

Taking moments about the point of application of the load

\[
M = H\rho = \int_0^{z_0} k_{so} \rho_z zdz - \int_0^{z_0} \frac{k_{so} \rho_z z}{q_{maxo}} dz
\]

where \( \rho_{z} = (z_0 - z) \tan \theta \) and \( \overline{\rho}_{z} = (z - z_0) \tan \theta \) are displacements above and below the point of rotation at depth \( z \), \( z_0 \) and \( \theta \) can be obtained by solving Eqs. (4) and (5).

The improved soil consists of subgrade modulus, \( k_{sh} \), and modulus of horizontal subgrade reaction, \( k_{so} \), and ultimate lateral soil pressure, \( q_{maxd} \). The variations of subgrade modulus and maximum soil pressure along the length of the pile are as shown in Figures 4(a) & (b) respectively. Based on these variations the force equation become

\[
H = \int_0^{L_d} k_{sh} \rho_z dz + \int_0^{L_d} \frac{k_{so} \rho_z}{q_{maxd}} dz - \int_0^{L_d} \frac{k_{so} \rho_z}{q_{maxo}} dz
\]

Fig. 4: Variation of (a) Horizontal Subgrade Moduli and (b) Ultimate Lateral Soil Pressure with Depth, \( z \)

The normalized equations for force and moment are

\[
H^* = \frac{H}{k_{sh} L^2} = \int_0^{\bar{z} \tan \theta} \frac{z}{1 + \mu_{sd} \bar{z} \tan \theta} dz + \int_0^{\bar{z} \tan \theta} \frac{(z - \bar{z})}{1 + \mu_{sd} \bar{z} \tan \theta} dz
\]

and

\[
M^* = \frac{M}{k_{sh} L^3} = \frac{H \rho}{k_{sh} L^2} = \int_0^{\bar{z} \tan \theta} \frac{z}{1 + \mu_{sd} \bar{z} \tan \theta} dz + \int_0^{\bar{z} \tan \theta} \frac{(z - \bar{z})}{1 + \mu_{sd} \bar{z} \tan \theta} dz
\]

where \( \bar{z} = z / L \) the normalized depth, \( \bar{z}_0 = z_0 / L \) normalized depth of point of rotation, \( L_d = L_d L \) and normalized load, \( H^* = H / \alpha_{sh} L^2 \). The parameters \( \mu_{sd} \) and \( \mu_{so} \) and the ratio, \( \alpha_{kr} \) are defined as \( \mu_{kr} = k_{sh} L / q_{maxd} = \alpha_{sh} L / \alpha_{qo} \), \( \mu_{so} = k_{so} L / q_{maxo} = \alpha_{so} L / \alpha_{qo} \), and \( \alpha_{kr} = \alpha_{sh} / \alpha_{so} \).

Ideally, the depth of rotation, \( z_0 \), and the rotation, \( \theta \), are to be estimated for given lateral force, \( H \), and moment, \( M \). However, it would be an iterative process and very tedious. For given values of \( \mu_{sd} \), \( \mu_{so} \), \( \alpha_{kr} \) and \( \bar{z}_0 \), and \( H^* \) can be obtained by solving Eqs. (7) and (8). Knowing \( \bar{z}_0 \) and \( \theta \), the normalized deflection at ground level, \( \rho^*_0 = \bar{z}_0 \tan \theta \), is evaluated corresponding to the normalized applied load, \( H^* \).

3. DISCUSSIONS

The variations of normalized load, \( H^* \), with normalized displacement at ground level, \( \rho^*_0 \), are evaluated based on the proposed model for different combinations of \( \mu_{sd} \) and \( \mu_{so} \).

Fig. 2: Non-Linear Hyperbolic Response of the Soil

Fig. 3: Variation of Parameters with Depth, \( z \) (a) Horizontal Subgrade Modulus (b) Ultimate Resistance

Fig. 4: Lateral Displacement Response of Piles Installed in near Surface Improved Coarse-Grained Soils
values ranging from 0 to 7000 with intermediate values of 10, 50, 100, 200, 500, 1000, 2000 and 5000; stiffness ratios, $\alpha_s$, of 50, 25, 10, 5, 2 and 1, normalised thickness of improved soil from ground level, $L_r$, varying from 0 to 0.7 and normalised load eccentricity, $e/L$ values spanning over 0, 0.2, 0.4, 0.6, 0.8, 1, 2 and 4.

Figure 5 shows the load versus displacement at ground level, $0.2, 0.4, 0.6, 0.8, 1, 2$ and $4$. The normalised load for a pile for depth of improvement $0.5L$, is about 200% compared to that prior to the improvement of the soil.

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The variations of normalised displacements at the top with normalised improved soil thickness and for different stiffness ratios, $\alpha_s = 10$ to 2 is illustrated in Figure 7 for $\mu_d = 1000$, $\mu_o = 1000$, $\theta = 0.01$, $e/L = 0$. The displacements of the piles at the ground line decrease with increase in $L_r$, for the case of stiffer upper surface. The displacement decreases from 0.0077 to 0.005 for $L_r$ increasing from 0 to 0.5, for $\alpha_s = 10$. The minimum value of displacement of the pile top depends on $\alpha_s$. For example, the normalised displacement is minimum near $L_r$ values of 0.5, 0.6, 0.67 and 0.7 for $\alpha_s = 10$, 5, 3 and 2 respectively. The percentage decrease in displacement is maximum at $L_r = 0.5$ for $\alpha_s = 10$. The maximum decrease in displacement occurs for $L_r$ between 0.5 and 0.7 for $\alpha_s$ in the range 10 to 2. The maximum decrease in displacement is about 32% for $\alpha_s = 5$.

Figure 6 presents the variation of normalised load with normalised displacement of the pile for different values of $\mu_d$ for $\mu_o = 2000$, $L_r = 0.4$, $e/L = 0$ and $\alpha_s = 5 – Effect of \mu_d$

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Figure 8 presents the normalised soil pressure distributions along the length of the pile, for different values of $\mu_d$ or $\mu_o$, $\mu_d = \mu_o$, $L_r = 0.4$, $\alpha_s = 5$ and $\theta = 0.01$. The normalised soil pressure below the depth of improved soil ($L_r$) is significantly less because it is 5 times weaker than the improved soil. The difference in normalised soil pressures between the curves for two values of $\mu_d$ is more in stiffened soil, while it is less in original soil.

The variations of ratio of ultimate lateral capacity the pile in improved soil to that in original ground ($H_{ud}/H_{wo}$) is also studied with respect to $L_r$, $\alpha_s$ and presented in Figure 9 for $\mu_d = 1000$, $\mu_o = 1000$, $L/d = 4$ and $e/L = 0$. The increase in normalised ultimate pile capacity is high for values of $L_r$ between 0 and 0.5. The ultimate lateral capacity ratio $H_{ud}/H_{wo}$ remains nearly constant for $L_r$ between 0.5 and 0.7 except for $\alpha_s = 10$. 

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Meyerhof et al. (1981) conducted tests on piles installed in two-layered soils. The dense and the loose sands have the following properties and conditions. Unit weights, $\gamma$, are 15.2 and 14 kN/m$^3$ and angles of internal friction, $\phi'$, are 50° and 35° respectively. Length of the pile, $L$, is 200.0 mm, diameter of the pile, $d$, is 12.5 mm, eccentricity of load ($e/L = 0$) and $L_r = 0.5$ and 0.75 for dense sand overlying loose sand. This data is applicable for the present problem and facilitates comparison of the present analysis with experimental results.

4. CONCLUSIONS

Present theory predicts the ultimate loads as well as the load-displacement responses at working loads of piles installed in densified ground. The displacements at ground line get reduced significantly as can be expected with increase in the stiffness of the near surface soil. The maximum decrease in pile top displacement occurs for $L_r$ between 0.5 and 0.7. The decrease in displacement is about 32% for stiffness ratio of 0.2. The predicted load-displacement plots compare well with the measured values reported by Meyerhof et al. (1981) for piles in two-layered soils. Not only displacement, but the ultimate carrying capacity of the pile in densified ground is also improved.

REFERENCES


Lateral Displacement Response of Piles Installed in near Surface Improved Coarse-Grained Soils